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COMPUTER PROGRAMS FOR PROCESSING SIGNALS RECEIVED IN

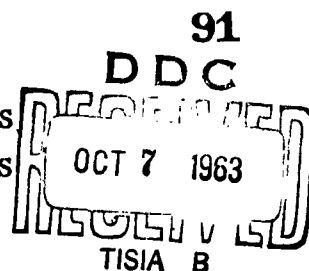RADAR ASTRONOMY EXPERIMENTS

P. L. Fleck, Jr.

T. J. Goblick, Jr.

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LEXINGTON   MASSACHUSETTS

COMPUTER PROGRAMS FOR PROCESSING SIGNALS

RECEIVED IN RADAR ASTRONOMY EXPERIMENTS

I. INTRODUCTION

In 1958, 1959, and 1961 experiments were conducted at this Laboratory to detect and study radar reflections from the planet Venus.[1,2] The received radar data were recorded on magnetic tape and analyzed on an IBM 709 (later a 7090) digital computer. The data of the 1958 experiments were processed using several special purpose computer programs. The 1959 and 1961 data were processed using the General Detection Program (GDP), a single computer program which had evolved from and effectively combined all the previously written programs.

The General Detection Program, which was written mainly in FORTRAN, is described in the first part of this report. We attempt to present enough of a general discussion of the capabilities of the GDP to aid in applying this program to other kinds of experimental data. Specific details of the operation of GDP are also given to serve as an operator's manual.

Section II of this report describes the basic Venus radar experiment. Section III deals with the data processing one should perform to maximize the signal-to-noise ratio of received radar echoes assuming the planet is a slowly fluctuating point target and the interference is additive gaussian noise. Section IV discusses how these operations are carried out by the computer. Section V gives a detailed list of the program parameters along with their use and format on input data cards, magnetic tape unit usage, and FORTRAN stops built into the program.

For the 1962 Venus conjunction the recording equipment was changed to reduce the operating time on the IBM 7090 by doing some of the data processing on a specially designed analog computer and recording the preprocessed data on magnetic tape. A modification of the General Detection Program was written to take advantage of this preprocessing. Section VI describes the new recording equipment and Section VII tells how the new program is to be used (hereafter called Multifrequency Program).
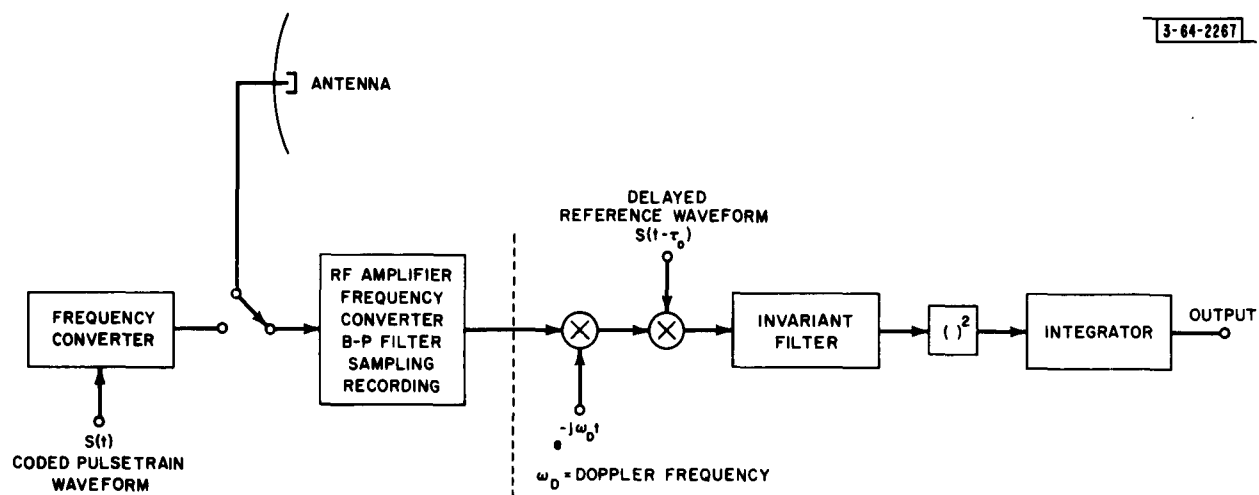
Fig. 1. Block diagram of the Radar System used for the Venus experiment

II.   THE EXPERIMENT

A block diagram of the radar system used in the Venus experiments is shown in Fig. 1. The transmitted waveform s(t) consists of a train of pulsed RF sinusoids which may be coded to provide unambiguous range information about the target. The coding, if used, is usually on-off coding of pulses or phase reversal according to a binary, linear shift register sequence.[3,4] The frequency of the sinusoids is up-converted to the operating frequency by very stable multipliers so that the pulse to pulse phase relations of the sinusoids is preserved. The pulse train is transmitted until the first transmitted pulse has been reflected by the planet and has returned to the earth (approximately 5 minutes for Earth-Venus when they are closest to each other). The transmitter is then turned off and the antenna is switched to the receiver. After amplification, down-frequency conversion, and band-pass filtering the received signal is in the frequency band between 0 and 7 kilocycles per second. The signal is then sampled at a 15 kcps rate, digitized using 6 bit quantization, and recorded on 7 channel 1/2 inch magnetic tape in standard IBM low density format (including longitudinal and latitudinal parity checks). One 36 bit IBM word on the tape, therefore, is composed of six data samples. When 2048 IBM words (12288 samples) of data are recorded, an end-of-record gap is written and the following 2048 words are recorded on the second tape recorder. This alternation between tape recorders continues until all the possible meaningful data are recorded (again, approximately 5 minutes).

The received operations indicated to the right of the dashed line in Fig. 1 are done by a digital computer. An IBM digital computer reads the data tapes directly and performs the data processing with absolute time-frequency stability. The computer program is designed to test hypotheses about signal location in time (target range), Doppler frequency shift and spread, and Doppler time rate of change experienced by the reflected signal. In Fig. 1 only a single range-frequency hypothesis is shown being tested (τ_0 seconds signal delay and ω_D Doppler frequency shift). The GDP is written to test up to 1000 range-Doppler hypotheses simultaneously in a single pass through the data tapes which reduces the computer time per hypothesis.
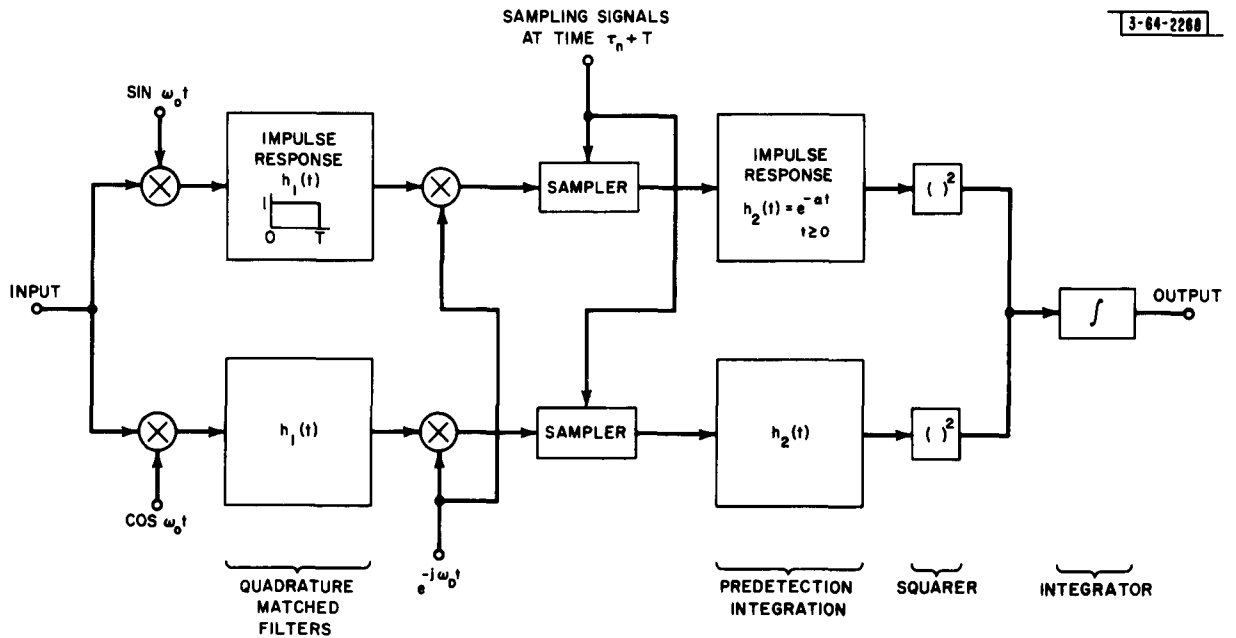
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Fig. 2. Radar receiver block diagram showing matched filters and pre-detection filters. The diagram is labeled for a train of pulsed sinusoids of duration T and of frequency $\omega_o + \omega_D$ with the nth pulse arriving at time $\tau_n = \tau_o + (n-1) \tau_{IPP}$, $n = 1, 2, \ldots$.

III.   RECEIVER DATA PROCESSING

For a slowly fluctuating point target, Price[5] has shown that the second multiplier and the invariant filter in the receiver in Fig. 1 may be interpreted as a filter matched to a transmitted pulse followed by a linear filter to combine some number of received pulses prior to squaring (pre-detection integration). This, along with the operations done by the GDP are shown in more detail in Fig. 2.

The transmitted pulse train is phase coherent in the sense that it is generated by gating a continuously running, stable oscillator. The received pulses arrive with some correlation of phase from pulse-to-pulse (as compared to the deterministic relation between pulse-to-pulse phases in the transmitted pulse train). Since the exact phase of any received pulse is unknown, the matched filter must consist of two quadrature filters matched to the sine and cosine components of the received pulse. If there were no pulse-to-pulse phase coherence in the received signal, the outputs of these two quadrature matched filters would be sampled at times $\tau_0 + (n-1) \tau_{IPP}$ corresponding to a τ_0 range hypothesis (τ_0 is the time of arrival of the first received pulse and τ_{IPP} is the received inter-pulse period), squared, and added into an integrator. This would be repeated for various τ_0 range hypotheses, and the integrator with the largest output corresponds to the best match of the reference signal to the received signal.

If there were complete phase coherence in the received pulse train, the matched filters should be matched to the sine and cosine components of the entire received pulse train; i.e., the matched filters would have impulse responses consisting of a train of pulsed sinusoids. For some degree of pulse-to-pulse phase coherence between these extremes of incoherent and perfectly coherent returns, the sampled outputs of the sine component matched filter should be combined for several successive pulses. The number of successive pulses thus combined before the squarer should correspond to the coherence time of the received pulse phase. The same should be done with the output of the cosine component matched filter.

In the GDP this pre-detection integration in each quadrature channel is accomplished by a filter whose output is an exponential weighting of all past matched filter outputs which is easily programmed by a recursion relation. It is reasonable to expect that the exact form of the weighting function is probably uncritical. The exponential damping is then adjusted to yield the desired amount of pulse-to-pulse pre-detection integration.

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The degree of precision required in specifying the total Doppler frequency shift depends on the amount of pre-detection integration used in the data processing, but inaccuracies in the ephemerides* and time standards may require testing several Doppler frequency hypotheses in order to detect the received signal and/or determine its spectrum. In practice, therefore, a coarse Doppler correction is introduced in the receiver frequency conversion equipment, and provision for processing an array of several different Doppler hypotheses is inserted into the program after the matched filter. The loss of signal detectability in placing the final Doppler correction at this point is negligible if the correction is much smaller than the bandwidth of the matched filter. Thus, the matched filtering need be done only once, prior to and independent of any actual hypothesis testing.

The actual receiver operations are carried out by a digital computer on sampled data, quantized in amplitude, but the previous discussion applies equally well in this case. In testing a single τ_0 range hypothesis the matched filter is sampled once each received inter-pulse period which produces a pair of numbers corresponding to the in-phase and quadrature components of a phasor. The fine Doppler correction of these samples then is carried out as an angular rotation of each phasor. The phasor corresponding to the nth sample of the matched filter is rotated $\omega_D(n-1)\,\tau_{IPP}$ radians, where τ_{IPP} is the duration of the received inter-pulse period. If the transmitted signal were coded, these phasors are multiplied either by +1 or 0, or by +1 or -1, according to whether on-off or phase reversal coding had been used. The multiplication is under the control of the same shift register that coded the transmission. The pre-detection filtering, squaring, and final integration for each hypothesis are carried out exactly as described above and after all the recorded data has been processed, the integrator outputs corresponding to all the τ_0 range and ω_D Doppler shift hypotheses are printed out.

The pulse duration is a parameter which is adjustable in GDP, as well as the received inter-pulse period and the center frequency of the matched filter. The GDP is written assuming the input data was sampled at 15 kcps, but since all the pertinent parameters of the pulse train are adjustable, data sampled at some other frequency can

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* The actual Doppler shifts can be predicted from astronomical tables to within a few cycles per second at the radar frequencies of the Venus experiment.

be scaled so that GDP can still do the data processing. For instance, a CW radar signal sampled at 7.5 kcps has been processed by the GDP.

IV. COMPUTER OPERATION

The computer processing may be broken down into two main parts. In Part I the recorded data is passed through the matched filter, and the output of this filter may be sampled a number of times within one inter-pulse period to later test for various time alignments of the received pulse train. These matched filter outputs may be recorded on auxiliary magnetic tape. Since no information concerning the detectability of the signal has been lost thus far, and since the bandwidth of the data has been reduced by the ratio of the matched filter bandwidth to the sampling frequency (typically 1/15), the data storage may be considerably compressed. If the range uncertainty is much less than an inter-pulse period, dense sampling of the matched filter output only in the time interval of interest also allows for reduced data storage. In Part II the matched filter outputs for all IPP's received are processed to test in one pass through the data various τ_o and ω_D hypotheses as explained above.

The basic unit of time measurement that the program uses is the received inter-pulse period (IPP) whose duration is a parameter (P1).[**] Starting with the very first data sample, the data is marked off in blocks which are equal in length to a received IPP. The exact time that the first data sample was taken is known, and P1 is used to calculate the exact time (in units of sampling intervals) (STAR) at which all following IPP's begin. These times are then rounded to the time at which the nearest data sample occurred.

In Part I, the first record of data is read into core storage and each IBM word is unpacked into 6 data samples, then processed in blocks marked off as described above. New records of data samples are read into core storage as needed. The amount of processing is specified as NK1 IPP's starting from the K$\emptyset$1[th] IPP. The computer then skips K$\emptyset$1-1 IPP's of data before starting its computations. The data samples are passed through a filter matched to a pulse of sine wave INT samples long (the frequency of the

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[**] The underlined symbols are the actual FORTRAN symbols used in the program to denote the quantities described.

sine wave is a parameter (FC1)), and the output of this filter is sampled periodically (A(*)).[†] (The actual starting point, spacing, and number of the samples of the filter output within an IPP can be varied (I∅1, MESH1, NJ1).)

The unknown phase angle of the received signal requires the use of a second matched filter with a pulse of cosine wave INT samples long as its impulse response. The output of the cosine filter is then sampled like that of the sine filter and these are the output data of each IPP processed by Part I (A(*), B(*)). This data can be recorded on tape and/or used directly by Part II as it is generated.

The large amount of recorded data (15,000 × 300 = 4.5 × 10^6 samples) demands that the above processing be done sequentially, which creates significant bookkeeping problems. It is obvious that in this type of data processing, the operations performed on every individual data sample must be considered carefully since on the 7090, each 2 cycle operation performed 4.5×10^6 times adds 19.6 seconds to the Part I processing time. This indicates that a good subroutine to generate sines and cosines for every sample (taking, say, about .1 ms per sine or cosine) would be exorbitant. To speed up the processing time a prestored sine table is generated and used in the following manner. The table contains arrays of 15 consecutive samples of sine and cosine functions of frequency FC1 quantized to 6 bits. There are 72 starting phase angles, one for every multiple of 5° from 0° to 355°. Phase angle (PHIO) is calculated for the first sample of every IPP from the IPP length (P1) and sine wave frequency (FC1) parameters. This phase angle is reduced modulo 360.0 and rounded to the nearest multiple of 5°, which loses no more than 2.5^o of accuracy. The program looks up the proper sine and cosine values for the first sample of the IPP, and then associates each of the following 15 values in the sine and cosine tables with the following samples in the IPP. When the 15 samples (corresponding to 1 millisecond of real time data) have been used, the exact phase angle is re-calculated, rounded off, and the program goes back to a new starting point in the table. The phase re-calculation is always performed at the beginning of each IPP.

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† A(*) refers to an array of a subscripted variable, similar to functional notation. A positive integer is allowed as the augment, *, by the computer.

Each data sample must be multiplied by the sine and cosine value, and this operation can be modified from the usual FORTRAN assembly by binary correction cards which make use of the variable-length multiplication instruction to take advantage of the fact that only 6 bit numbers are involved.

An actual convolution of the data samples with pulsed sinusoids is not done by the computer. Instead, every data sample of an IPP is multiplied by a sine (JSN(*)) and a cosine (JCS(*)) wave yielding a pair of products (JDA(*), JDB(*)); then the convolution of each of these product sets with a D. C. pulse INT samples long is computed. This convolution is quickly performed since one has only two operations to perform in shifting this rectangular pulse and integrating. The oldest product term is subtracted out of the sum and the newest one added in. Consider the array of JDA(j), j = 1, 2, ..., N. The convolution of these products with a 2 msec[‡] D. C. pulse is merely a sum of 30 consecutive products.

$$JAP(k) = \sum_{j=k}^{k+29} JDA(j) , \quad k + 29 < N.$$

It is clear that

$$JAP(k+1) = JAP(k) + JDA(k+30) - JDA(k)$$

and the program computes the complete convolution of all the data with pulsed sin and cos waves. In order to save time, the convolution is done in fixed point arithmetic and the only points of the convolution to be converted to floating point numbers for recording or use by Part II are those specified by the parameters IØ1, MESH1, and NJ1, which refer to the first point of the convolution, the spacing, and number of points to be floated respectively.

Part II combines the corresponding samples of the Part I matched filters for all IPP's, thus testing the hypotheses of a particular location of the entire received pulse train.

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‡ For the examples that follow, it is assumed that a 2 msec pulse (INT = 30) was transmitted and the round trip travel time is 300 seconds.

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Let us examine the Part II processing for the simple case of an uncoded pulse train that is known to have no appreciable pulse-to-pulse phase coherence in the received carrier (NSW = 8). For example, suppose the samples of the Part I matched filter have been taken every 1 msec (MESH1 = 15) for the entire length of an IPP. To get a measure of the signal energy contained in the first two milliseconds of an IPP the computer takes the sum of the squares of the very first samples in the IPP of the sine and cosine filters. The energy in the 2nd and 3rd millisecond interval of the IPP are found from the second pair of samples of the sine and cosine filters, etc. The energy contributions of corresponding 2 msec intervals of the IPP's are summed, starting with a given IPP (KØ) until the pulse energies from the prescribed number of IPP's (NK) have been added together. These final totals are the Part II output. Since this particular signal is uncoded and many pulses (about 15,000) are sent, there will be a range of starting IPP's which give almost the same final output. The target range, therefore, can only be measured modulo P1 seconds, a result of transmitting an uncoded radar waveform.

Instead, suppose an on-off coded sequence was sent and there was no pulse-to-pulse coherence (NSW = 5). The only difference from the previous situation is that before adding energy contributions of "2 msec intervals of a particular IPP" (henceforth called range boxes), the shift register* sequence is checked to see if this particular pulse was actually sent or not. If it was sent, things are added as before, and if it was not, the energy contribution for that particular IPP is just noise, so it is not added to the cumulative sum of pulse energies.

This coding provides a larger final output if the SR coding is matched exactly to the received sequence of pulses. This is due to the auto-correlation properties of SR sequences. Correct alignment implies that Part II processing begins in the IPP which contains the first received pulse. If an array of these runs is done, each starting with a different IPP (but using the same shift register sequence), the run with the largest output will determine the absolute range.

The range resolution is a function of the S/N of the received signal, and the motion of the target relative to the earth, but the limit to which this program can determine round trip travel time is 1/15 millisecond (the time between data samples).

Now suppose we wish to take advantage of pulse-to-pulse coherence in the received signal which lasts roughly over 10 pulses. We now want a filter which will add together

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* Abbreviated SR.

roughly 10 pulses before the energy calculation (squaring) is done. The first thing that is done with the Part I outputs for each range box is to form a cumulative sum for each of the sin and cos terms, but every time the contribution of an IPP is added, the sum of the past IPP's is multiplied by a factor (DCR) less than 1. This provides an exponential weighting of past pulses and in our case we would use a number for DCR that becomes small with respect to 1 when it is raised to the 10th power. The pulse contributions from the far past would then be attenuated and the pulse-to-pulse coherence would help to build up the signal relative to the noise before squaring. From this point on, the squaring and post-detection integration is the same as before (Note: any pulse decoding must be done before the pre-detection integration).

The passband of the Part I matched filter is exactly (2/INT) times the sampling frequency between the first zeros of the $\frac{\sin x}{x}$ spectrum (1 kcps for the case of 15 kcps sampling and 2 msec pulse) and so there is no reason to retune the Part I filter for very slight changes in its center frequency (which means doing Part I again). The amplitude of the $\frac{\sin x}{x}$ spectrum is nearly constant over a small range of frequencies around the center frequency. The Doppler frequency shift of the received signal is usually known to within several cps and so rarely must a frequency correction greater than this be made. Part II is able to actually make corrections in the carrier phase every IPP and thus achieve the effect of a matched filter center frequency slightly removed from the actual FC1 used.

Suppose we wish to process the data with the Part I matched filter retuned 1.0000 cps higher than that which was used to make Part I auxiliary tape. We use the Part II frequency parameter

$$\underline{F} = \underline{FC1} + 1.0000$$

and the program will, at the start of every IPP, calculate the phase difference between the frequencies FC1 and F. Then the Part I outputs for every range box, considered as sine and cosine components of a phasor, are rotated (ahead in this case) to make up for the phase difference between the old center frequency and the new, desired one. Then Part II processing proceeds as before.

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To take into account a change in Doppler shift during the received signal, the Doppler shift at the end of the run is compared to that at the beginning of the run. The Doppler shift is then assumed to be a linear function through these two points with the parameter FCHG giving the cps/second change in Doppler. Part II then calculates the actual phase at the beginning of every IPP of this slow frequency sweep of the carrier and corrects the Part I output for the phase difference between FC1 and the carrier in the same manner as F is handled.

It is clear from the above that incoherent processing implies that no fine change in center frequency and/or change in Doppler need be taken into account.

Up to this point, some terminology associated with these programs has been introduced. One further addition to the vocabulary is useful. A "run" refers to an array of range boxes within the IPP that is tested with the beginning of the processing specified as a particular IPP (KØ). Twenty simultaneous "runs" can be processed by Part II; the only parameters that cannot be varied for each run are the number of pulses to be processed and the starting point of processing with regard to the SR code. That is, processing will always start with the NSRth number of the SR sequence for coded runs. Thus, for example, one can then do a range search with range boxes spaced 1 msec apart and with each of the 20 runs starting in a different IPP (KØ(*)). One can also specify different range box patterns for the different runs and have all start in the same IPP (varying IØ(*), NJ(*), MESH(*)). (Part I must be able to accommodate this, i.e., if the matched filter is sampled only once every msec, there is not enough data to make a Part II run looking at range boxes 1/2 msec apart.) Or, one can do a frequency-range search, viz., 20 runs with the same NJ range boxes but with separate "coherent" matched filters centered on different frequencies spaced FDEL apart, each filter with the same FCHG. Or, by punching separate parameter cards, up to 19 different runs, each with an independent F, FCHG, DCR, KØ, IØ, NJ, and MESH can be processed at the same time.

Almost all of the program parameters have been mentioned in the text thus far (also some program names for internal variables). The remaining parameters are discussed in Section V, and mainly refer to the detailed format of the output data.

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VENUS RUN 12 JUNE 21,1963 1340 EST   CARD 1

COLUMN 1 IS NOT READ

.060014528	4218.2500	16	1	60	15	30	15020	1	CARD 2
P1	FC1	Kϕ1	Iϕ1	NJ1	MESH1	INT	NK1	NT1	

15000	10	7500	20	0	0.250	1	1	1	CARD 3
NK	NOUT	NTSK	NARY	NSR	FDEL	KEY	NS		

123456

.060014528	4210.0000	16	31	5	15	1	.952	-0.001200	CARD 4
P	F(1)	Kϕ(1)	Iϕ(1)	NJ(1)	MESH (1)	NSW (1)	DCR(1)	FCHG(1)	

CARDS 5,6,7 MUST BE BLANK

Fig. 3.   Card Parameters for General Detection Program

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V. GDP PROGRAM PARAMETERS

Although the program was written assuming the sampling frequency would be fixed at exactly 15,000 samps/s (F SAMP), the program can be used with data sampled at any frequency simply by properly scaling P1, FC1, INT, FDEL, F, DCR, and FCHG by the ratio of the true sampling frequency to 15 kcps.

DATA CARDS   See Fig. 3.

CARD 1 contains any BCD information (identifying title), (column 1 is not sensed by the machine).

CARD 2 contains the Part I processing parameters. If Part I is recorded (NS1 ≠ Ø), any further use of these Part I tapes requires the use of the same Part I card that generated them.

CARD PARAMETERS:

P1(F1Ø.9)[††] The expected period of the returning signals in seconds. This parameter is the key one that is used to mark off the data in inter-pulse periods by the calculation of STAR + (P1 * 15,000). The storage arrays will not accommodate a value of P1 exceeding 0.066 with INT = 30 or .064 w/INT = 60.

FC1(F1Ø.4) Center frequency of the matched filter in cps. The first zero crossings of the $\frac{\sin x}{x}$ spectrum of this filter are fixed 2 * (sampling frequency)/INT cps apart. This parameter is used as the frequency of the sine wave by which the data is multiplied. The phase angles PHI, JPHI, and KPHI are calculated from FC1. FC1 must be less than 7000 cps because the sampling rate is fixed at 15,000 cps to avoid spectral overlap. FC1 is used to calculate the sine table since it together with the sampling rate determines the sine wave phase for consecutive data samples.

KØ1 (I1Ø) The starting inter-pulse period as calculated from the first data sample. This is used to advance past worthless data. For the 1959 Venus equipment the first 15 IPP's are samples of the end of the transmitted waveform, therefore, KØ1 was always 16 or larger.

IØ1 (I5) This number is the first sample of each IPP that will be processed, and corresponds to the leading edge of the first integration pulse. IØ1 must be less than 15,000 * P1, the number of samples in an IPP.

NJ1 (I5) This is the number of range boxes processed per inter-pulse period. This number must not process data more than 100 samples past the end of an IPP due to the size of the storage array.

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†† The symbols in parentheses are the actual symbols used in the FORMAT statements used to read these cards. From these it is easy to determine how the cards should be punched.

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<u>MESH1 (I5)</u> This is the number of samples by which the range boxes are spaced. If the sampling frequency is 15 kcps, the MESH1/15 is the spacing in time (msec). MESH1 can range from 1 to 15. Making it larger than 15 gives inadequate information about the received pulses. The only samples which are multiplied by the sine and cosine and integrated are those required by I$\emptyset$1, NJ1, and MESH1. The integrated samples are called JA and JB. The only JA and JB quantities that are floated for recording on tape are the NJ1 samples specified by I$\emptyset$1 + j * MESH1 for j = 0, 1, ... , NJ1-1 and so only these A's and B's may be used by Part II processing when Part I is <u>not</u> recorded. (NJ1-1) * MESH1 + INT + I$\emptyset$1 must not exceed 1025 due to limited storage array size.

<u>INT (I5)</u> The number of samples which are added together to make the Part I matched filter. INT should be the nearest integer to the length of the received pulse in terms of samples.

<u>NK1 (I1$\emptyset$)</u> The number of inter-pulse periods (IPP) to be processed and recorded per reel of output tape.

<u>NT1 (I1$\emptyset$)</u> The number of output tapes on Channel B, starting with B1. The total number of IPP's processed by Part I will then be NK1 * NT1. An output record has 2 * NJ1 + 3 words per IPP, and the length required per IPP (in inches) is:

$$\left(\frac{2 \times NJ1 + 3}{127} \right) * \left(\frac{128 \times 6}{B} + \frac{3}{4} \right) + \frac{3}{8}$$

B = Recording bit density (200 or 566) bit/inch. Each full reel has 28,800 inches. This determines NK1 and the amount of data will determine NT1.

CARD 3 Contains the Part II parameters that are common to all Part II runs.

CARD PARAMETERS

<u>NK(I1$\emptyset$)</u> This is the number of IPP's integrated for each run. The number NK and MAXK must be less than NK1 * NT1 when using pre-recorded Part I. There is no limit on NK if Part I is done with Part II, i.e., NS2 = 0, except that NK < 32,768, a FORTRAN constraint.

<u>NOUT (I1$\emptyset$)</u> This is the number of IPP's for which the complete Part I outputs are written in BCD on tape A4. Usual numbers are from 0 to 10.

<u>NTSK (I1$\emptyset$)</u> The contents of the NJ integrators are printed out for the IPP's: K$\emptyset$ + (NTSK) * j for j = 0, 1, ... up to the final IPP which is also printed out. Also, the value of the input to the integrators at that IPP along with the difference from the last NJ integrators is printed. This output is on tape A4 in BCD.

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<u>NARY (I5)</u> If NS6 $\neq$ 0, an array of NARY consecutive KØ's are processed (starting with KØ). This is used for coded searches and gives up to 20 runs with only one Card 4. If NS5 $\neq$ 0, an array of NARY different pre-detection filters are processed (starting with F). NARY must not exceed 20.

<u>NSR (I5)</u> This initializes the locally generated shift register. NSR of 0 starts the shift register at its preset alignment. NSR of 1 = NSR of 2^n where n is the number of stages in the shift register. This parameter is used only for coded processing and the numbers used must not be negative. Negative numbers can be made positive by expressing them as their counterparts in the modulo $2^n - 1$ system. KØ is chosen to correspond to the first inter-pulse period which contains a usable received pulse. NSR is chosen to correspond to the position in the sequence of this first usable pulse.

> <u>e.g. 1</u> The return of the first transmitted pulse is judged to be within the 18th inter-pulse period of recorded data counting inter-pulse periods from the beginning of the tape. The KØ = 18 and NSR = 0.

> <u>e.g. 2</u> The return of the first transmitted pulse is judged to be within the 6th inter-pulse period but the first 30 inter-pulse periods are not usable due to some equipment malfunctions. Then the first 25 received pulses (from the 6th to the 30th IPP inclusive) are not usable. KØ = 31 but now NSR = 25, since the 26th pulse of the sequence is the first usable one.

> <u>e.g. 3</u> Suppose the first transmitted pulse is judged to arrive in the fifth IPP before recording began (N = −4). If the first 15 IPP's on tape are useless, then 20 pulses of the sequence are neglected. KØ = 16 and NSR = 20.

<u>FDEL (F1Ø.4)</u> This determines the spacing of the NARY filters (above) in cps. Normally, FDEL will be less than the bandwidth dictated by DCR. FDEL must be positive.

<u>KEY (I1Ø)</u> If sign of KEY is +, one file will be skipped on A2 and A3 at the start. The first word in every record will be skipped if $|KEY| = 1$. If it is left·blank (− 0) data will be expected in 1959 Format (2048 word records).

<u>KRAP (I6)</u> A dummy parameter to space the NS(j) to the last 6 columns on the card.

<u>NS(j) (I6)</u> Any punch in column 66 + j, j = 1 to 6, will have the effect of making NS(j) $\neq$ 0 (See Table below). The physical sense switches on the computer are not used.

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NS USAGE

NS1   Making $\neq 0$ will cause the program to record the results of Part I on NT1 tapes B1, B2, ..., B(NT1).

NS2   Making $\neq 0$ causes the program to do only Part II using the results of pre-recorded Part I B tapes.

NS3   Not used.

NS4   This inhibits the rewind on A2 and A3, if $\neq 0$.

NS5   Making $\neq 0$ causes the program to read <u>FDEL</u> and <u>NARY</u> on Card 3 and do an array of <u>NARY</u> runs, starting at <u>F</u> and spaced <u>FDEL</u> cps apart.

NS6   Making $\neq 0$ causes the program to read <u>NARY</u> on Card 4 and do an array of <u>NARY</u> runs, starting at <u>KØ</u> and spaced 1 IPP apart. NSR is fixed for each run.

If both NS5 and NS6 are zero, the program reads in as many Card 4's as are present (19 maximum) and processes that many runs.

All 72 columns are used on this card.

CARD 4   Contains the Part II parameters for each separate run. One can use up to 19 cards, by they must be followed by 3 blanks.

CARD PARAMETERS

<u>P(F1Ø.9)</u>   Not used.

<u>F(F1Ø.4)</u>   Center frequency of the Part II pre-detection filters in cps. This F should have values of FC1 $\pm$ 500 cps in order to lie within the pre-filtering of the signal by Part I. The output of this Part II filter will be almost periodic with a period 1/P1, so there is no need of searching over a wider region.

<u>KØ (I1Ø)</u>   This is the starting inter-pulse period for this Part II run. (See KØ1 and NSR). KØ should be no smaller than KØ1. When using different Card 4's for different runs, the maximum allowable difference between the largest and smallest KØ is 20.

<u>IØ (I5)</u>   This is the starting sample corresponding to the leading edge of the first range box. IØ <u>must</u> be in the following set of numbers:

$$IØ1 + j * MESH1, \quad j = 0, 1, \ldots, (NJ1 - 1).$$

If not, the alignment of the floated numbers will be incorrect and zeros will result in the output.

NJ (I5)   The number of range boxes that will be processed by Part II and printed out on Tape A4. NJ must not be zero, nor larger than 50 or NJ1, whichever is smaller.

MESH (I5)   This has the same meaning as MESH1, but applies for this Part II run only. MESH must be an integer multiple of MESH1. In general, when using I$\emptyset$, NJ, and MESH, they must be selected to align with the processed Part I output.

NSW (I5)   This determines the type of processing for this run according to the following table:

NSW	CODING	PRE-DETECTION FILTERING
1	Uncoded	Coherent
2	S.R. on-off	Coherent
3	S.R. phase-rev	Coherent
4	S.R. + −	Incoherent
5	S.R. on-off	Incoherent
6	Anti S.R. on-off	Incoherent
7	Anti S.R. on-off	Coherent
8	Uncoded	Incoherent

FCHG (F12.6)   This introduces a linear rate of change of F (above) with time of FCHG cps/s. A negative FCHG will decrease F while a positive FCHG will increase F with time. At K$\emptyset$, the center frequency of the filter will be F and it starts changing at this time.

DCR (F1$\emptyset$ 8)   The 3 db bandpass bandwidth of the Part II pre-detection filter is:

$$-\frac{\ln DCR}{\pi P1} \quad (cps)$$

The range of DCR is from 0 to 1. Using 1 corresponds to infinite memory (zero bandwidth) i.e., weighting the past uniformly. A zero DCR corresponds to no memory or incoherent processing. For incoherent processing the program is more efficient if NSW = 8. F, FCHG, and DCR are used only for coherent processing (i.e., NSW = 1, 2, 3, or 7).

CARD 5, 6, 7.   These must be blanks.

TAPES

A1 The Program Tape--"GDP w/VLM 6, June 1963" Push Load Tape to start processing.

A2 The data tape with the first (and all succeeding odd numbered) records.

A3 The data tape with the second (and all succeeding even numbered) records. The records are 2048 IBM words long. These data tapes are not needed if $NS2 \neq 0$.

A4 Blank for BCD output. To be printed off line, under program control.

B1, B2, ... NT1 tapes, blanks if Part I is to be recorded, $NS1 \neq 0$, or pre-recorded tapes if Part II only is to be done ($NSL \neq 0$). These tapes are not needed if $NS1 = NS2 = 0$. The tape units may be used in the high density mode if using a $7\emptyset9\emptyset$.

RUNNING TIMES FOR NK = 15,000 ON THE $7\emptyset9\emptyset$

$NSW = 8$, $NJ = 27$, $MESH = 15$, Part I & II: Time = 31 min.

$NSW = 8$, $NJ = 405$, $MESH = 1$, Part I & II: Time = 60 min.

$NSW = 8$, $NJ = 27$, $MESH = 15$, Part II only: Time = 6 1/2 min.

$NSW = 2$, $NJ = 2$, $MESH = 15$, $NF = 20$, Part II only: Time 17 min.

$NSW = 5$, $NJ = 4$, $MESH = 15$, $N\emptyset K\emptyset = 3$, Part II only: Time = 9 min.

BINARY DECK: General Detection Program dated 28 September 1961 (with 4 binary correction cards) RTRB, NUSHI, SHIF, VENUS (NEW), CON (B11) subroutines. Note: Use the NUSHI and SHIF subroutines which are applicable to the data to be processed, i.e., programmed versions of the shift register used to code the transmission.

STOPS (in octal):

HPR 77777 Good Final Stop

HPR 111 A data tape has an RTT. (Read twice) Push start to accept the dubious data and continue

HPR 7 Input-Output Check Test is on for Channel A.

HPR 303 End of File is on for Channel A.

HPR 77077 A data tape has a record of incorrect length. Push start to accept the dubious data and continue.

NSTOP = 7Ø7Ø7 A data card has an incorrect parameter.

NSTOP = 123 NJ1, IØ1, and MESH1 need too large an array for the Part I multiplications.

NSTOP = 321 Not enough 1 millisecond multiplications done.

NSTOP = 7ØØ Incorrect number of records on the B tapes.

NSTOP = 1234 NJ > 50

NSTOP = 12 NARY > 20. There are more than 19 Type 4 cards, or 1 or more of the following are ≤ 0: IØ1, INT, NJ1, KØ1, MESH1, NK1, NK, KØ, IØ, NJ, MESH or NSW.

NSTOP = 71Ø Incorrect number of tapes (NT1).

NSTOP = 720 KØ is less than the K recorded on tape, or K does not agree with KR recorded.

NSTOP = 77 The sample number that has been calculated is negative.

NSTOP = 7Ø1ØØ Cannot write on B tape--fix up NK, NT1, NK1.

NSTOP = 25 NOUT is negative.

NSTOP = 77ØØ KTAG is negative, KPR (M1) > NTSK, MD is negative, or ITAG3 is negative.

NSTOP = 222 Maximization of range box is incorrect.

NSTOP = 111Ø Alternation of data tapes is incorrect.

NSTOP = 12345 Part II and Part I are misaligned--change IØ, MESH, NJ.

NSTOP = 77777 Final Stop.

TRANSFER

If program stops, or if a read out of what has been done is required, (before a natural ending occurs) TRA 4256$\big|_8$. The output value given for K may be off by 1.

VI.   1962 EQUIPMENT

Figure 4 shows a block diagram of the pre-processing equipment. The heart of the system is the Time Computer which effectively takes the variables P1, FCHG, and FC1 out of the program (assuming a correct ephemeris is used to pre-calculate these values). This Time Computer is a special purpose analog computer which predicts when the signal is received at each IPP. Therefore, only a fraction of the data around the time of interest need be recorded instead of recording the data continuously. Further,

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ROUND TRIP TRAVEL
TIME   FCHG   FC1

SLEWED CLOCK PULSES

TIME STANDARD → TIME COMPUTER

P1 PULSES

ANTENNA

ADJUSTABLE
SAMPLING
FREQUENCY

TIMING
CIRCUITS

LOCAL OSCILLATOR
INJECTION FREQUENCY

RADIO RECEIVER
AND
FREQUENCY
CONVERTER

DC

2 ANALOG
MATCHED
FILTERS

DC

A-D
CONVERTER

GATE

CORE
MEMORY

INTERFACE

TAPE
RECORDER

RF

DC

DC

QUADRATURE
CHANNELS

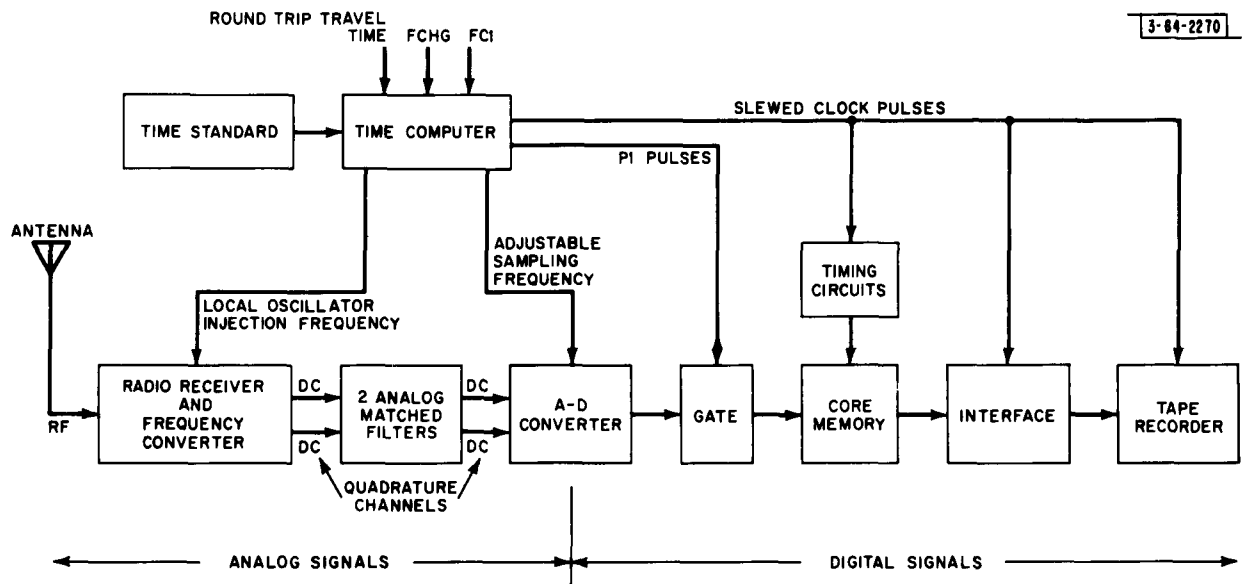◄──── ANALOG SIGNALS ────►   ◄──── DIGITAL SIGNALS ────►

Fig. 4.   1962 Radar Preprocessing Equipment

this computer takes the doppler and rate of change of doppler out of the received signal which simplifies the bookkeeping and obviates the need of using FCHG in the program. (The Multifrequency program does, however, have provision for FCHG.)

The received signals are amplified and converted to d.c. in the radar receiver by means of local oscillator injection frequencies which match the changing frequency of the received signals. Only a linear rate of change of frequency is provided with a precision of .03 cps. This corresponds to a precision of 2 parts/10^{11} referred to the transmitted pulses (the carrier frequency is 1295×10^6 cps). The accuracy is limited by the time standard (typically a few parts/10^{10}).

As in GDP two quadrature channels are carried along, each of which passes through an analog low pass filter matched to the width of the transmitted pulse. The two filter outputs are digitized to 3 bits each by A-D converters which are sampled at a rate corrected by the ratio of the transmitted IPP to the received IPP. These digital signals pass through a gate which is opened by a pulse which preceeds each received pulse by a preset time which remains constant throughout the run. When the gate opens, a selected number (≤ 720) of pairs of samples are stored in a core memory, with the received pulse always being stored at the same core location (hence, sample number) in each IPP. The capacity of the core is 720 pairs of samples, and every 60 m.s. the entire core is read out via the interface onto one tape record (120 IBM words in each record corresponding to 720 pairs of 3-bit samples). The tape is edited with a separate program by an edit factor n which depends on the number of samples/IPP and the length of the IPP; i.e., $n - 1$ records out of every n records are deleted. (For example, if the IPP is nominally 60 msec and the number of samples/IPP = 720, there is no editing required; but if the IPP is 30 msec with 72 samples/IPP, 4 out of 5 records are deleted.) This editing can result in a considerable compression of data. For example, it is possible to record over one hour of real time data on one reel of tape. The resultant tape is similar to (but not interchangeable with) the B tapes that are generated by GDP.

VENUS RUN 12 JUNE 21,1963 1340 EST   CARD 1

COLUMN 1 IS NOT READ

| .060014523 | 1 | 6000 | 3000 | 10 | +1 | 50 | 0.3000 | | CARD 2 |
| PI | KΦ1 | NR | NTSK | NIPP | NSKIP | NARY | FDEL | MERR | |

| -7.60000 | 4 | 69 | 1 | .9500 | -0.000120 | | | CARD 3 |
| F(1) | IΦ(1) | NJ(1) | MESH (1) | DCR(1) | FCHG(1) | | | |

CARDS 4,5,6 MUST BE BLANK

Fig. 5. Card Parameters for Multifrequency Program

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VII. MULTIFREQUENCY PROGRAM PARAMETERS

The Multifrequency program has no provision for shift register coding, but other-wise it can do everything else the GDP Part 2 can do. The running time is slightly faster than GDP since it reads data which is 12 times more densely packed. The program parameters have the same meaning, with two exceptions (KØ1 and NTSK). Also, the NS1-6 are not used. All the parameters will now be discussed in order as they appear on the data cards.

DATA CARDS   See Fig. 5.

CARD 1.   Contains any BCD information (column 1 is not sensed by the program).

CARD 2.   PARAMETERS

P1 (FlØ.9)   The expected period of the returned signals. This is used only to calculate the phase of the rotating phasors. If the transmitted IPP is used, F and FCHG will be in error by the ratio of the doppler to the carrier frequency--generally a negligible error.

KØ1 (IlØ)   The program will skip KØ1-1 records (not IPP's) on the data tape and start processing the KØ1st record. This number must be less than 32768.

NR (IlØ)   NR records will be processed. This is equivalent to processing NR * NIPP inter-pulse periods. NR must be less than 32768.

NTSK (IlØ)   Intermediate output dumps of all the integrators are printed out after processing every NTSK records(not IPP's) and after NR records have been processed. Also, the value of the input to the integrators at that time, along with the differences from the previous intermediate dumps will be printed out. NTSK must be greater than 0.

NIPP (I5)   This is the number of IPP's per record on the data tape. It is equal to 720/number of samples per IPP. It is not the edit factor.

NSKIP (I5)   If left blank, the data tape will be rewound at the beginning and end of the program. If NSKIP = + 1, the data tape will never be rewound.

NARY (I5)   An array of NARY different pre-detection filters are generated and processed. NARY must not exceed 50. If NARY = 0, the program will process as many runs as there are card 4's. (49 maximum).

FDEL (FlØ.5)   This determines the spacing of the NARY filters (above) in cps. Normally, FDEL will be less than the bandwidth dictated by DCR. FDEL must be positive.

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MERR (I7)   This is the maximum number of errors allowed in reading the
data tape Bl. If the sign of MERR is +, the program will skip the record
sequence checking routine and count only RTT's. If the sign of MERR
is − (e.g. left blank) both RTT's and bad record sequences are counted
as errors. When the number of errors exceeds MERR the computer
will stop. (H PR 111). Pushing Start will cause the computer to accept
the data and continue; however, any single future error will result in
a stop H PR 111 ad infinitum.

CARD 3   PARAMETERS

F (F1$\emptyset$.5)   This is the center frequency (in cps) of the pre-detection filter
for this run. If NARY > 0, this will be the frequency of the lowest
frequency in the array, the others being incremented by FDEL. Since
the input data is at d.c. (zero frequency) F may be negative. Due to the
periodicity of the transmitted signal, there is no need of searching over
a region greater than 1/P1.

I$\emptyset$ (I5)   The first output number will be the result of processing the I$\emptyset^{th}$
sample in each IPP. Since the first three samples have coding data,
I$\emptyset$ will generally be 4 or larger.

NJ (I5)   The program will process NJ samples. NJ must not exceed 72, but
must be greater than 0.

MESH (I5)   This is the spacing (in terms of samples) between the NJ output
range boxes. The samples processed will be:

$$I\emptyset 1 + (j - 1) * MESH, \ j = 1, 2, \ldots, NJ.$$

The recorded data must have at least this many samples/IPP.

DCR (F15.1$\emptyset$)   The 3 db bandpass bandwidth of the pre-detection filter is:

$$\frac{- \ln (DCR)}{\pi(P1)} \quad cps$$

The range of DCR is from 0 to 1. Using 1 corresponds to infinite
memory (zero bandwidth). If DCR = 0, there will be no memory
(incoherent processing) and there is no need for NARY, F, FCHG,
etc.

FCHG (F12.7)   This introduces a linear rate of change of F (above) with time
of FCHG cps/s, starting with K$\emptyset 1^{st}$ record. FCHG may be of either sign.

CARDS 4, 5, 6   These must be blank.

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TAPES

A1   The program tape--"Multifrequency, June 1963" Push "Load Tape" to start processing.

A3   Blank for BCD output--to be printed off line, program control.

B1   Data Tape as prepared and edited by the Millstone 1962 Radar Equipment or equivalent--EOF at beginning of tape and data records 120 words long.

The subroutine UNPAC skips one file and one record at the beginning to get into the good data (often the data tapes have a spurious record at the beginning). The first 6 bits in every record are used as a count-of-64 counter and the program will check each data record for proper sequencing unless the sign of MERR is positive. The second 6 bits in the first good record (i.e., no RTT's) is printed out as the run number.

RUNNING TIMES FOR 7094

1) $NARY = 10$, $NJ = 72$, $NIPP = 10$, 2 seconds/data record

2) $NARY = 50$, $NJ = 72$, $NIPP = 10$, 9.5 seconds/data record

3) $NARY = 5$, $NJ = 20$, $NIPP = 10$, 0.37 seconds/data record

4) $NARY = 12$, $NJ = 40$, $NIPP = 10$, 1.36 seconds/data record

5) $NARY = 0$, $NJ = 72$, $NIPP = 10$, $DCR = 0$, 0.19 seconds/data record

OCTAL STOPS

$NSTOP = 12$ K$\emptyset$1, NK, I$\emptyset$, NJ, and/or MESH ≤ 0
or $NARY > 50$
or there are more than 49 card 4's.

$NSTOP = 222$ NL < 1 or the maximization of range boxes is incorrect.

$NSTOP = 1234$ NJ > 72

$NSTOP = 77\emptyset\emptyset$ KTAG < 0 or NTSK $<$ KPR

$NSTOP = 7\emptyset7\emptyset7$ I$\emptyset$, NJ or MESH too large

$NSTOP = 77777$ Good Final Stop

HPR 77777   Good Final Stop
HPR 111   The tape on B1 has just made more than MERR errors.

ACKNOWLEDGEMENT

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